

Validity and Accuracy of Regional Bioelectrical Impedance Devices to Determine Whole-Body Fatness

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OBJECTIVE: Growing emphasis on obesity as a risk factor for chronic diseases and commercial availability of impedance devices for the at-home assessment of body fatness have stimulated the need for a critical evaluation of the validity of these instruments. This study determined the reproducibility and accuracy of two commercial impedance devices that use upper (hand-to-hand) or lower (foot-to-foot) body contact electrode placements in adults with a wide range of body fatness.

METHODS: Body composition was assessed with dual x-ray absorptiometry in apparently healthy adults (62 women and 48 men) ages 21 to 60 y, with a range in body mass index of 18.6 to 40.5 kg/m². Variability in body fatness predicted with the regional body impedance devices was determined in 10 adults on 5 consecutive d. A 50-kHz, tetrapolar bioelectrical impedance plethysmograph with surface electrode placements on the upper and lower limbs was used to determine reference regional and whole-body impedance values.

RESULTS: Variability in body mass (1%) over 5 d was less than body fatness predicted with the upper (2–10%) and lower (3–5%) body devices. Regional and whole-body impedance values were different ($P < 0.05$) in the women, whereas upper and lower body values were lower ($P < 0.05$) than whole-body impedance in the men. Dual x-ray absorptiometric determinations of body fatness were similar to predictions based on models derived from physical characteristics (age, stature, body mass, and sex) but significantly different ($P < 0.05$) from estimates from the impedance devices, which underestimated body fatness. Bias in predictions of body fatness with the regional devices was systematically ($P < 0.0001$) related to body fatness.

CONCLUSION: Use of regional impedance devices to assess body fatness is limited by a lack of precision and accuracy. *Nutrition* 2003;19:851–857. ©Elsevier Inc. 2003

KEY WORDS: human, body composition, dual x-ray absorptiometry, fat percentage

INTRODUCTION

Overweight and obesity are increasing at alarming rates throughout the world.^{1,2} As public health organizations seek to increase awareness of the health hazards of these conditions, there is an emphasis on the use of body mass index (BMI) as an indicator of overweight and obesity.³ As an indicator of body fatness, BMI is appealing because it uses practical measurements of body mass and standing height. However, it is limited in accuracy because it is a non-specific measure of body fatness for an individual.^{4,5} There is a need for a practical, reliable, and accurate method for determining body composition.

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Tetrapolar bioelectrical impedance is one technique that may meet this need in healthy individuals.^{6,7} Although this approach is safe, it requires the application of adhesive electrodes on one hand and one foot, the use of a current-introducing and voltage-sensing electronic device with the individual in a supine position, and an operator of the device. These factors limit the use of whole-body impedance instruments for personal use.

Recently, there has been an interest in developing tetrapolar impedance devices that use contact electrodes and measure lower body impedance to estimate body composition of humans.⁸ Some investigators have extended this application to include upper and lower body determinations of impedance to estimate whole-body composition.^{9–12} The attraction of this use of regional impedance is its practicality and convenience for routine, personal monitoring of body composition at home. With the generalized use of regional impedance measurements to predict whole-body composition, assumptions that conductor volume is equally distributed in the upper and lower body and that regional impedance reflects whole-body impedance^{13,14} are questionable. Further, there is a paucity of data describing the reliability, validity, and accuracy of the devices that measure regional impedance and estimate whole-body composition.

We report the reproducibility of body fatness estimates derived from commercial devices that determine regional impedance and the accuracy of these estimates of whole-body composition. We also test the hypothesis that differences in the distribution of body

TABLE I.

PHYSICAL CHARACTERISTICS OF THE SUBJECTS				
	Females*	Range	Males*	Range
<i>n</i>	62		48	
Age (y)	40.6 ± 1.4*	21–60	39.2 ± 1.5	22–52
Mass (kg)	70.1 ± 1.6	51.0–106.8	85.8 ± 1.9	61.5–120.8
Height (cm)	164.7 ± 0.7	148.4–180.3	179.2 ± 1.0	161.3–203.3
BMI (kg/m ²)	25.8 ± 0.5	18.7–40.5	26.7 ± 0.6	18.6–35.5
Body fat (%)†	37.5 ± 1.2	15.2–54.5	22.7 ± 1.2	6.7–42.4

* Mean ± standard error of the mean.

† Dual x-ray absorptiometry.

BMI, body mass index

compositional components affect the estimation of body composition in healthy women and men.

MATERIALS AND METHODS

We recruited apparently healthy adults from the community. A nurse screened the applications, including a self-reported medical history, and determined eligibility for participation. Exclusion criteria included pregnancy, chronic disease, and use of medications that influence fluid balance and metabolism.

This study was approved by the Institutional Review Board of the University of North Dakota School of Medicine and Health Sciences. Participants gave written informed consent after receiving written and oral descriptions of the purpose, risks, and benefits of the study.

One aspect of this research determined the variability of the regional impedance predictions of body fatness as opposed to body mass. Ten adults, five women and five men, underwent determinations of body mass and predictions of body fatness with the upper and lower body impedance devices as described below.

Volunteers came to the laboratory 1 to 2 h after consumption of a meal. They wore standardized clothing (e.g., pants and shirt). Body mass (± 0.2 kg) was determined without shoes or socks with a calibrated scale (model 2831, Toledo Scale, Worthington, OH, USA). Standing height or stature (± 0.1 cm) without shoes was measured with a stadiometer (Harpender, Pembroke, UK) mounted on a wall.

Validation of the regional impedance predictions of body fatness used dual x-ray absorptiometry as the reference in 110 adults (Table I). Body composition was determined by using a pencil-beam dual-energy x-ray absorptiometer (QDR 2000-W, Hologic, Waltham, MA, USA). Each subject wore standardized clothing without shoes. Scan images were analyzed for soft tissue composition by using Enhanced Whole-Body Analysis 5.73. For each subject, the individual dual x-ray absorptiometry scan was used to distinguish upper from lower body composition. A horizontal line was drawn at the superior iliac crest (Fig. 1); areas inferior to the line were designated as the lower body, and anatomy superior to the line was characterized as the upper body.

Standard procedures were used to control artifacts in the impedance measurements.¹⁵ Subjects were advised not to engage in strenuous physical activity for 24 h before scheduled impedance measurements. Because dual x-ray absorptiometry determinations of body composition were performed first, all subjects rested in a supine position for at least 20 min in a temperature-controlled room before any impedance measurements were made.

All bioelectrical impedance measurements were made in random order. Regional bioelectrical impedance was determined by using commercial instruments. Lower body impedance was mea-

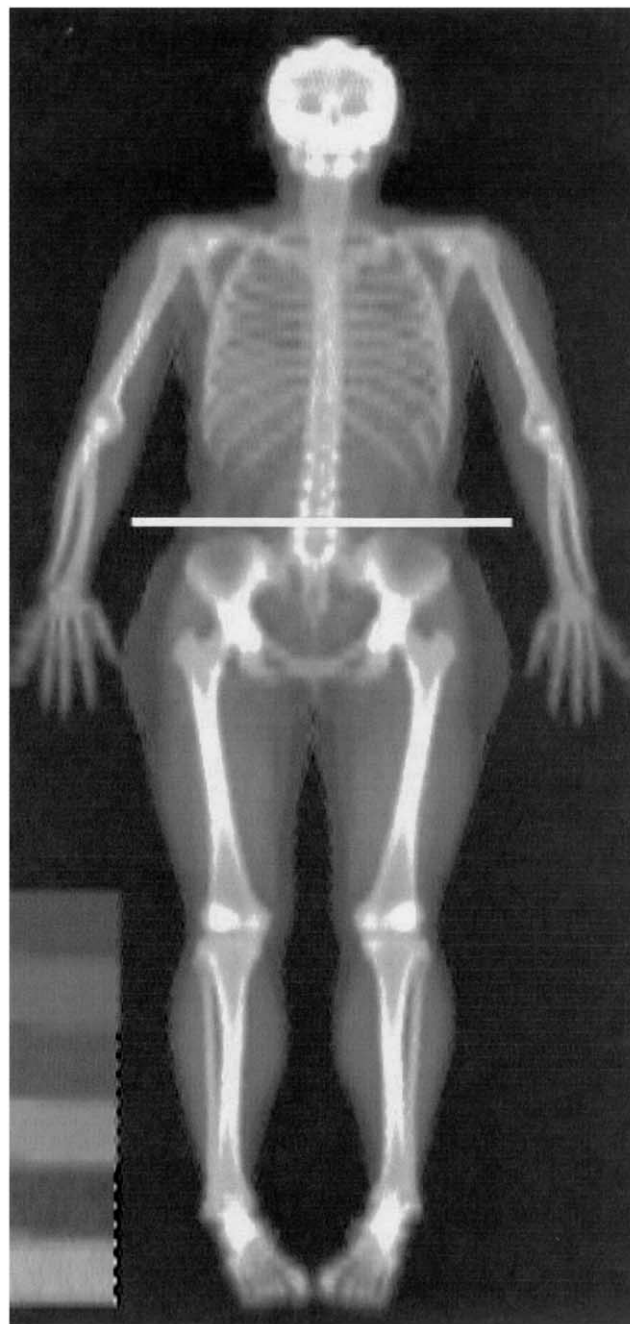


FIG. 1. Dual x-ray absorptiometry scan with a designation of upper and lower body components. The area superior to the horizontal line drawn across the iliac crest is the upper body and the area inferior to the line is the lower body.

sured with a Tanita TBF-604 Body Fat Monitor/Scale (Tokyo, Japan). This device requires the input of data describing the body mass, standing height or stature, and sex of the subject who then stands on the scale, which contains the source and detector electrodes in the areas that contact the plantar surfaces of both feet. It measures lower body impedance and then calculates the body fatness (fat percentage). Upper body impedance was determined with an Omron Body Fat Analyzer HBF-301 (Vernon Hills, IL, USA), which contains source and detector electrodes in the hand grips. This device also requires the individual to enter her or his physical characteristics (e.g., mass, stature, age, and sex); it then measures impedance of the upper body before calculating body

TABLE II.

CHARACTERISTICS OF THE SAMPLE USED TO GENERATE THE ANTHROPOMETRIC MODEL TO PREDICT BODY FATNESS

	Females*	Range	Males*	Range
<i>n</i>	244		137	
Age (y)	37.7 ± 0.7*	27–60	39.8 ± 0.8	20–58
Mass (kg)	69.7 ± 0.8	50.2–103.8	85.8 ± 1.9	62.8–120.4
Height (cm)	164.8 ± 0.6	154.7–180.6	178.4 ± 0.6	164.7–198.9
BMI (kg/m ²)	25.6 ± 0.3	18.6–37.9	25.8 ± 0.5	18.9–34.9
Body fat (%)†	36.5 ± 0.6	14.9–54.8	21.7 ± 0.7	6.2–43.8

* Mean ± standard error of mean.

† Dual x-ray absorptiometry.

BMI, body mass index

fatness. The subject grips the device with both hands and then extends the hands away from the body while the impedance is determined. These devices use proprietary equations to calculate body fatness.

Each subject also underwent determinations of whole-body and regional bioelectrical impedance by using a single-frequency (800 μ A at 50 kHz), four-electrode impedance plethysmograph (model 101-A, RJL, Clinton Township, MI, USA). Calibration of the device was confirmed with a precision electrical circuit that included a resistor (500 Ω ± 0.2%) and a capacitor (0.05 μ F ± 1%) in a series/parallel electrical circuit before measurement of each subject. We measured whole-body resistance and reactance with adhesive, spot electrodes positioned on the right foot and hand, after these sites were cleaned with alcohol, with the volunteer supine on a non-conductive table surface.¹⁵ Regional bioelectrical resistance and reactance also were measured. Lower body (e.g., foot-to-foot placement) measurements were performed with source and detector electrodes positioned on each foot as described for the whole-body determinations. Upper body (e.g., hand-to-hand) determinations were accomplished with electrodes placed on both hands, similar to the arrangement described for the whole-body measurement. Impedance was calculated as $[(\text{resistance})^2 + (\text{reactance})^2]^{1/2}$.

Because the regional impedance devices use prediction models that include body mass, stature, age, sex, and the impedance measurement of an individual, we evaluated the independent contributions of these self-reported physical characteristics to estimate body fatness. We used dual x-ray absorptiometry soft tissue composition data from volunteers in other studies with the objective of developing a regression model derived from their physical characteristics to predict body fatness in healthy adults. We selected the sample by using the following criteria for age (±3 y), body mass (±3 kg), height (±5 cm), and body fat (±3%) and matched these to each subject (*n* = 110) in the experimental group (Table I). This approach yielded a sample of 381 adults (Table II).

Data are presented as mean ± standard error of the mean. Reproducibility, reported as the coefficient of variation ([standard deviation/mean] × 100%), of the regional impedance predictions of body fatness was determined in 10 adults measured on 5 consecutive d. Reference body fat estimates were compared with regional impedance measurements by using linear regression analysis.¹⁶ Linear regression analysis also was used to develop models to predict body fatness from physical characteristics in the independent sample.¹⁶ Comparison of body fatness values determined from the regional impedance devices, regression models using physical characteristics, and dual x-ray absorptiometry were examined with a repeated measures experimental design by using one-way analysis of variance.¹⁶ When a significant main effect was identified, comparisons across methods were made with Tukey-

TABLE III.

REFERENCE WHOLE BODY AND REGIONAL IMPEDANCE VALUES (O) IN 110 ADULTS*

	Female†	Male†	Range
Upper body	610 ± 8 ^{Hf}	460 ± 8 ^b	283–795
Lower body	516 ± 9 ^d	440 ± 8 ^a	299–747
Whole body	589 ± 7 ^e	475 ± 8 ^c	306–720
Analysis of variance			
Root MSE			21.6
Sex			<i>P</i> < 0.0001
Position			<i>P</i> < 0.0001
Sex × position			<i>P</i> < 0.0001

* Values with different superscripts are significantly different (*P* < 0.002).

† Values are mean ± standard error of the mean.

MSE, ??

Kramer contrasts with adjustments for multiple comparisons.¹⁶ If a significant interaction was found, Bonferroni contrasts were performed.¹⁶

The method of Bland and Altman¹⁷ was used to further assess the agreement between methods. Differences between individual regional impedance predictions and dual x-ray absorptiometric measurements of body fatness were plotted against the mean of the two measurements to determine bias. The precision of estimated body fatness from the regional impedance devices for an individual was expressed as bias ± 1 standard error of the mean.

RESULTS

The variability in estimating body fatness differed by device. Over a wide range of body weights (64–108 kg), the upper body impedance device yielded a range of predicted body fatness values (22–30%) that was similar to that found with the lower body instrument (17–34%) in the 10 adults. During the 5-d trial period, the variability in body weight was minimal (1%). The reproducibility of predicted body fatness, however, was more variable with the upper (2–10%) than with the lower (3–5%) body instrument.

The distribution of body composition, determined by dual x-ray absorptiometry, was comparable in the women and men. The ratio of lower to whole-body mass was similar for the women and men (49.9 ± 1.3 and 50.2 ± 0.8%, respectively). Fat-free, bone-free mass was similarly distributed among the females and males (51.2 ± 2.4% and 49.3 ± 1.0%, respectively). However, relatively more body fat mass was located in the lower body region of the women than that of the men (58.9 ± 1.6% versus 51.0 ± 1.0%, respectively; *P* < 0.001). Thus, a sex-dependent distribution of fat was found.

Impedance measurements were significantly affected by a sex × body region interaction (Table III). Impedance values were significantly different in each placement site within and between each sex. Lower body values were significantly lower than measurements in the other sites. However, upper body values were significantly higher than whole-body values in the women, whereas whole-body values were significantly higher than upper body values in the men.

Regional and whole-body impedance values were significantly related (Fig. 2). Upper body impedance was correlated with whole-body measurements in women (*R*² = 0.803, *P* < 0.0001) and men (*R*² = 0.830, *P* < 0.0001). Similarly, lower body impedance was

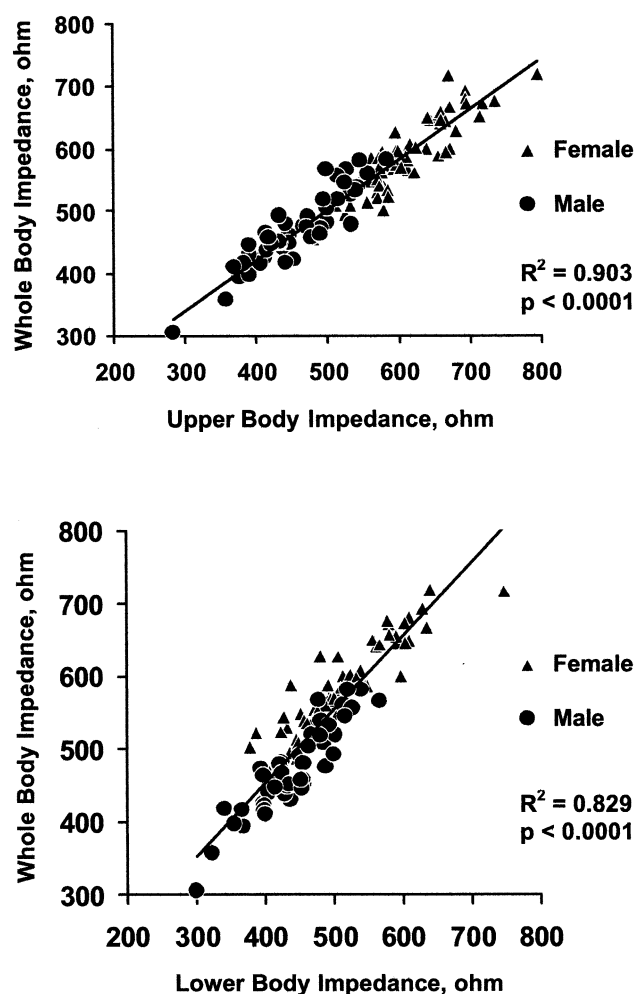


FIG. 2. Relations between upper and whole-body impedance (upper panel) and lower body and whole-body impedance (lower panel) in 110 adults.

correlated with whole-body values in women ($R^2 = 0.812$, $P < 0.0001$) and men ($R^2 = 0.831$, $P < 0.0001$).

Because the regional impedance devices derive fatness values without providing impedance data, we used a calibrated impedance plethysmograph with specific electrode arrangements to determine upper and lower body impedances. Regional impedance values were significantly ($P < 0.0001$) correlated with dual x-ray absorptiometry determinations of whole-body fatness. Upper body impedance measures explained similar amounts of variability in predicting body fatness in the women and men (67% versus 62%); similar results were found with the lower body impedance measurements (61% and 62%). However, more variance in the relation between upper and lower body impedance was explained in the women than in the men (67% versus 50%).

Regression models were developed to predict body fatness from physical characteristics in an independent sample of adults (Table II). The regression model for the prediction of body fatness using physical characteristic data entered into the upper body impedance device is:

$$\% \text{fat} = 63.65 + 0.52 \text{ body mass} - 0.42 \text{ stature} \\ + 0.15 \text{ age} - 15.20 \text{ sex}$$

$$R^2 = 0.78, \text{ standard error of the estimate} = 5.14$$

with body mass in kilograms, stature in centimeters, age in years, and sex coded as 1 = male and 0 = female.

TABLE IV.

COMPARISON OF BODY FATNESS (%) DETERMINATIONS*		
	Women†	Men†
<i>n</i>	62	48
DXA	37.5 ± 1.2^a	22.7 ± 1.6^b
Upper body	31.2 ± 1.0^e	20.4 ± 1.1^d
Bias‡	$-6.3 \pm 0.8 $	$-2.3 \pm 0.4 $
Regression§	37.2 ± 0.8^a	23.9 ± 1.1^{bc}
Bias‡	$-0.3 \pm 0.1 $	$1.2 \pm 0.1 $
Lower body	34.9 ± 0.9^f	24.4 ± 1.2^c
Bias‡	$-2.6 \pm 0.9 $	$-1.7 \pm 0.3 $
Regression§	36.7 ± 0.8^a	22.7 ± 1.0^{bc}
Bias‡	-0.8 ± 0.3	0.0 ± 0.3
Analysis of variance		
Root MSE		3.3
Sex		$P < 0.0001$
Position		$P < 0.0001$
Sex \times position		$P < 0.0001$

* Values with different superscripts are significantly different ($P < 0.05$).

† Mean \pm standard error of the mean.

‡ Bias = (regional impedance prediction - DXA).

§ Prediction model derived from physical characteristic data specific to each device.

|| $P < 0.05$; H_0 : bias = 0.

DXA, dual x-ray absorptiometry; MSE, mean square error.

The prediction model for the lower body device is:

$$\% \text{fat} = 76.22 + 0.53 \text{ body mass} - 0.46 \text{ stature} - 15.54 \text{ sex}$$

$$R^2 = 0.76, \text{ standard error of the estimate} = 5.37$$

with units of measure the same as those described above.

Body fatness determinations were significantly affected by a sex \times body region interaction (Table IV). In general, dual x-ray absorptiometric determinations of body fatness were not different from values predicted with the regression models but were significantly different from values predicted with the regional impedance devices. Further, each regional impedance device yielded significantly different estimates of body fatness. Body fatness determined with each regional impedance device was significantly different from the predicted value derived from the regression model when using the specific physical characteristics in conjunction with the measured impedance.

The distribution of the errors in prediction of body fatness plotted as a function of the mean body fatness values shows a systematic effect with increasing body fatness determined with the upper ($P < 0.0006$) and lower ($P < 0.0006$) body impedance devices (Fig. 3). Further, the errors in predicting fatness are consistently and significantly related to region-specific body fatness (Fig. 4).

The precision of estimating body fatness with each regional impedance device was large (Table IV). The variability of individual estimates of body fatness were larger (-2.6% to -6.3% fat) in the women than in the men (-1.7% to -2.3% fat). These errors were reduced from -0.8% to -0.3% fat in the women to 0% to 1.2% fat in the men with the use of the regression models derived from physical characteristics.

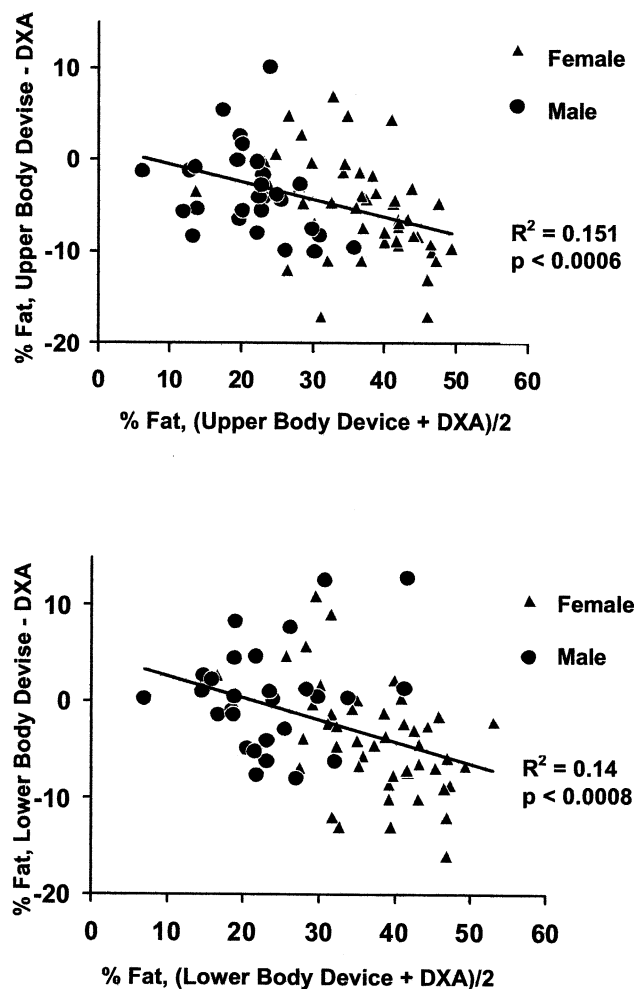


FIG. 3. Relations between errors (DXA and regional impedance predictions) and mean values of body fat (%fat) in 110 adults. DXA, dual x-ray absorptiometry

DISCUSSION

The availability of commercial impedance devices has followed the increase in public awareness of the epidemic of overweight and obesity and the desire to monitor personal body composition. Although these devices are appealing because of their relatively low cost and convenience of use, their validity in estimation of body composition has not been rigorously evaluated. We report that factors such as poor reproducibility, lack of validity, and high variability in individual estimations of body fatness hamper the generalized use of these devices.

There is only limited information describing the short-term reproducibility (coefficients of variance) of regional impedance devices. Nunez et al.⁸ reported a within-day variability of about 1% and a between-day variability of 2.1% in determining impedance with a foot-to-foot device. Because the impedance devices used in the present study did not show impedance values and because physical characteristics did not change ($\pm 1\%$) during the 5-d evaluation period, we used body fatness predictions to estimate variability of the impedance devices. The variability estimates ranged from 2% to 10% for the upper body device and from 3% to 5% for the lower body device. These differences in precision are not biologically important in the context of regional impedance measurements, which exceeded 500 Ω in the previous⁸ and current studies but also exceeded the usual variability (1%) in standard whole-body impedance measurements.⁶

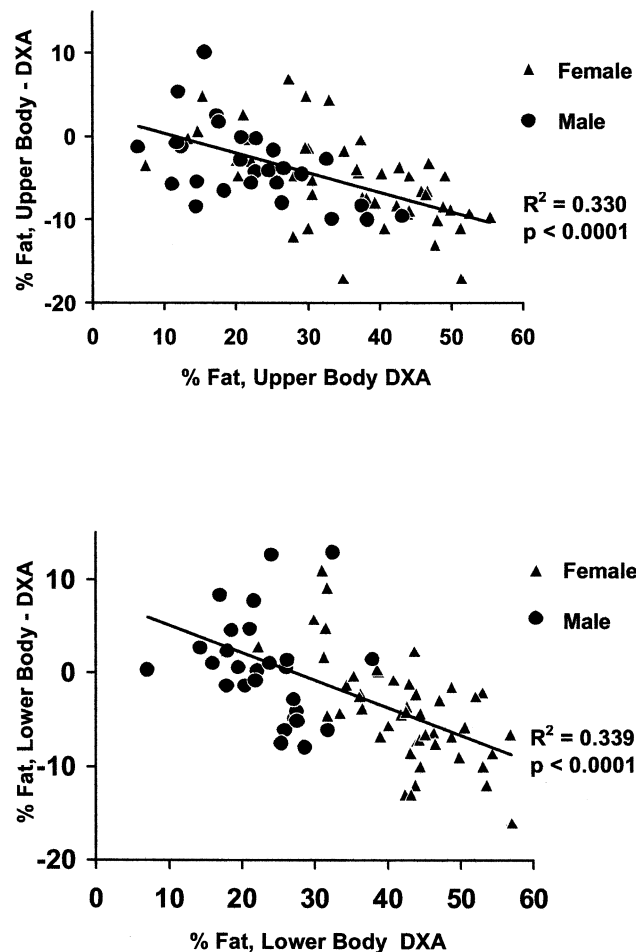


FIG. 4. Relations between errors (DXA and regional impedance predictions) and regional body fat (%fat) in the upper (upper panel) and lower (lower panel) body in 110 adults. DXA, dual x-ray absorptiometry.

Measurements of regional body impedance consistently are different from whole-body determinations. Although the regional and whole-body impedance values are significantly correlated, a significant difference among them has been found. Nunez et al.⁸ found in women and men that foot-to-foot or leg-to-leg impedance values were significantly greater (15 Ω) than whole-body measurements. Comparisons of regional and whole-body impedance measurements in children have shown even greater disparities. Foot-to-foot impedance measurements were consistently more than 100 Ω less than those determined with whole-body determinations when using a right-hand to right-foot electrode placement in a sample of 34 boys and girls ages 8 to 11 y.¹⁸ Similarly, foot-to-foot resistance was approximately 100 Ω less, and hand-to-hand resistance was more than 100 Ω greater than whole-body resistance measured in more than 200 prepubertal children.¹⁹ These observations suggest that different bioconductors were measured or that body geometry may be an uncontrolled factor. Our data indicated a sex \times region interaction. In the women, impedance values were significantly less in the lower body impedance than in the whole-body impedance, which was significantly less than upper body values. In contrast, upper and lower body values were not different but significantly less than whole-body measurements. This finding indicated that regional differences in bioelectrical impedance are influenced by sex and affect the validity of the regional impedance devices to accurately predict the body composition of an individual.

One explanation for the observed differences in regional impedance may be found in the distribution of the bioelectrical

conductor in the upper and lower body. Fat-free, bone-free mass, however, was similar in the women and men. Although absolute values were significantly different in women and men, the relative distributions of the biological conductor (e.g., percentage of total mass) were similar at 51% and 49% for the women and men, respectively. Thus, other factors may be involved.

We evaluated the accuracy of the regional impedance devices by comparing them with a reference method, dual x-ray absorptiometry, and regression models based on physical characteristics. Use of the regression model was prompted by the need to include these variables when impedance was measured with the devices. Analyses showed that the devices per se significantly underestimated body fatness, except for the lower body device, which overestimated it in men (Table IV). In women and men, the upper and lower body devices estimated significantly different values of body fat. Importantly, the regression models produced body fatness estimates that were similar to the values determined with dual x-ray absorptiometry. This observation indicated that demographic and anthropometric variables are more predictive of body fatness than is the combination of regional impedance and these variables in these instruments.

It is noteworthy that the lower body as opposed to the upper body impedance device yielded estimates of body fatness closely related to reference values of body fatness. This finding is consistent with the findings of Nunez et al.²⁰ and Utter et al.⁹ who used the foot-to-foot impedance method to determine regional body composition.

One factor that may explain the errors in predicting body composition with the upper body device is consistent contact with the contact electrodes in the hand grips. In contrast with the foot pad electrodes, which probably have full contact with the plantar surfaces of the feet when the individual is standing, the contact electrodes in the hand grips require a consistent, voluntary squeezing of the grips. If full contact with the electrodes in the hand grips is not accomplished, variability in measured impedance may occur with an interrupted circuit between the current-introducing and voltage-measuring electrodes.

Examination of the errors in predicting body fatness with regional devices when compared with dual x-ray absorptiometry showed a systematic effect of fatness (Figs. 3 and 4). Specifically, as total body or regional body fatness increases, the regional devices significantly underestimate body fatness. This finding suggested that differences in the composition (e.g., the relative distribution of fat and fat-free, bone-free masses) of a body segment affect the validity of the bioelectrical impedance method to estimate body composition. Organ et al.²¹ provided data in support of this contention and concluded that the use of regional resistivity may overcome this limitation. Recently, Biggs et al.¹¹ used lower body impedance, estimated segmental resistivity, and determined regional body composition in healthy adults. Thus, this approach may be useful in future applications.

Advances in bioelectrical impedance instrumentation may overcome these limitations. Miyatani et al.¹⁰ developed a system that measures upper and lower body impedances simultaneously. This system uses a 50-kHz alternating current and contact electrodes in hand grips and the thigh. Validation trials showed excellent congruence in estimates of muscle mass with magnetic resonance imaging. Thus, this new approach may be useful in future applications of body composition assessment.

Another concern with these regional impedance devices is the reliance on proprietary formulae to predict body fatness. The lack of a public declaration of the regression model limits the application of the models in different segments of the population. For example, it is unclear if the findings of significant bias in the present study can be explained by sample specificity in body composition (e.g., differences in body fatness) in the sample used to develop the prediction model and the sample of adults in the present study. Moreover, the validity of these proprietary models may be questioned in individuals with fluid expansion or dehydra-

tion. It is noteworthy, however, that the derived model for prediction of body fatness generated with demographic information (e.g., standing height, body mass, age, and sex) similar to that required in the proprietary models yielded values of body composition similar to the determinations from dual x-ray absorptiometry. Thus, questions persist about the robust nature of the proprietary formulae.

The potential of regional bioelectrical impedance remains attractive. Reliability of the upper and lower body devices is slightly greater yet comparable with traditional adhesive electrode instruments. However, there is concern with the lack of accuracy when compared with a standard reference method. Recent developments in types of electrodes and their placements may be successful in overcoming the limitations of currently available regional impedance devices.

CONCLUSION

The practical characteristics, such as ease of operation and privacy, of commercial regional impedance devices to assess whole-body composition are hampered by a lack of accuracy. Errors in the prediction of body fatness are significantly influenced by whole-body and regional (e.g., upper and lower body) fatness. It is unknown whether these regional impedance devices are valid instruments to assess changes in body composition.

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